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Integrated management approaches for pink bollworm in the southwestern United States

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The pink bollworm (PBW), *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae), is the key pest in cotton (*Gossypium* spp.) production areas in the southwestern United States and in many other cotton-producing areas of the world. The high costs of chemical control, continuing economic losses, secondary pest problems and environmental considerations suggest the need for ecologically oriented PBW management strategies. Extensive research has resulted in a broad array of monitoring, biological control, cultural, behavioural, genetic and host plant resistance methods that can serve as a base for the formulation of integrated PBW management systems. The life history characteristics of the PBW, in particular the high mobility of adults, indicate the need for combinations of selected integrated pest management (IPM) components implemented over large geographical areas. The areas involved present a wide range of PBW population densities, differences in cotton production methods and social and environmental considerations. The best option is tailor-made systems for targeted management areas with the selection of IPM components based on the PBW population density, crop production methods and economic feasibility. The unlikelihood of eradication indicates the need for long-term monitoring and programme maintenance following successful area-wide management. The success of area-wide PBW management is highly dependent on participation in the planning, site selection, implementation and assessment phases of the programme by all segments of the agricultural community. A highly effective extension–education communication programme is an essential component. Local uncoordinated efforts have not reduced the economic status of this pest in any area where it is an established pest. The potential long-term benefits of PBW population suppression on an area-wide basis appear to justify area-wide efforts in terms of reduced costs, more effective control, less environmental contamination and other peripheral problems associated with conventional control approaches.

Keywords: Pink bollworm; IPM; control; management strategies.

Introduction

The pink bollworm (PBW), *Pectinophora gossypiella* (Saunders), was described by W.W. Saunders in 1842 from specimens damaging cotton in India. More recent studies suggest the origin of the PBW as the eastern Indian Ocean area bordered on the east by northwestern Australia and on the west by various islands of Indonesia-Malaysia (Common, 1958; Wilson, 1972). It is generally believed that the insect reached Egypt in infested cotton seed from India about 1906–1907. It was introduced into the Western hemisphere between 1911 and 1913 in cotton seed shipped from Egypt to Brazil, Mexico, the West Indies and the Philippine Islands (US Department of Agriculture, Animal and Plant Health Inspection Service, 1977). A recent review by Ingram (1994) provided a worldwide perspective on PBW pest status and management.

Infestations in the United States first occurred in Texas cotton in 1917 and the source was traced to 1916 cotton seed shipped from Mexico to Texas oil mills (Spears, 1968; US Department of Agriculture, Animal and Plant Health Inspection Service, 1977). Cotton-free zones and extensive clean-up measures eliminated the Texas infestation and an infestation found in Louisiana in 1919. Reinvasions in 1936, probably from windborne moths from Mexico, occurred in the lower Rio Grande Valley of Texas, eventually spreading by the mid-1950s to other areas in Texas, New Mexico, Oklahoma, Arizona, Arkansas and Louisiana. Infestations were reported in eastern Arizona in 1926 and at intervals thereafter in other parts of the state. These infestations were suppressed through cooperative federal, state and industry programmes. The termination of these efforts in 1963 resulted in spread to the Imperial and Palo Verde Valleys of California in 1965. Severe losses had occurred by 1967 in Southern California cotton production areas. Moths were detected in the high desert areas of Los Angeles and San Bernardino Counties in early 1967 and moths and larvae were found in cotton in the San Joaquin Valley near

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Bakersfield later that year. Native moths have been trapped in the San Joaquin Valley each year since, except for 1968 and a few larvae have also been found in some years. However, as of 1997, the San Joaquin Valley remains the only cotton-growing area in Arizona and California without a firmly established PBW population. This is partially explained by extensive cultural control, PBW pheromone monitoring and a sterile moth release system initiated in 1968 (see Henneberry (1994) for a review). However, other factors, such as differences in the environmental conditions, even if established, suggest fewer generations and a lower PBW population development potential as compared with the lower desert, cotton-growing areas of the far west. Climatic adaptability is an unknown possibility.

Economics

Cotton growers in Arizona and southern California have experienced severe economic losses from the PBW due to reduced yields, low lint quality and the increased costs of insecticides (Watson and Fullerton, 1969; Burrows *et al*., 1982). Losses from infestations in the Imperial Valley, California alone ranged from 8 to 79% of the crop value from 1966 to 1980 (Burrows *et al*., 1982). More recently, Gonzales (1990) reported that the mean cost of insecticide use in Imperial Valley during 1978–1988 was \$640 ha^{-1}. The cotton yield and quality losses and insecticide costs for PBW control and reduced cotton prices in the world market were the major factors resulting in reduced cotton production from 57 871 ha in 1977 to 3713 ha in 1994 in the Imperial Valley (Chu *et al*., 1996). Although, similar information is not available regarding the relationship between the PBW and cotton acreage in Arizona, the insect has been a major factor affecting cotton production costs since the early 1960s.

The need for alternative approaches

Chemical control has not provided a long-term solution for the PBW problem because of the high costs, environmental impact and related problems (insecticide-resistant insect strains, the reduction of pest insect natural enemies, the resurgence of pest populations in the absence of natural enemies and the occurrence of secondary pests). Insecticide control focuses on attacking localized populations on a farm by farm basis. In contrast to this approach, area-wide suppression and management has evolved with our increasing awareness of the limitations of attacking local infestations which represent only a small part of the total pest population (Knipling, 1979). It seems clear that the PBW and other key pests of cotton in the southwestern United States could be significantly reduced through area-wide management approaches. The successful development and implementation of an area-wide management programme will depend on a complete understanding of the pest biology and ecology and knowledge of how to integrate the wide array of available cultural, chemical and biologically based suppression tactics into an effective management system.

In this paper we review the basic biology, ecology and population dynamics of the PBW and the current tactics and options available for the management of this pest in the southwestern United States. We then summarize several programmes that have incorporated a limited number of integrated pest management (IPM) components into community-action programmes for PBW management and discuss considerations for the development and implementation of area-wide management programmes based on the integration of various control tactics.

Biology, ecology and population dynamics

Life history

PBW adults are greyish-brown moths approximately 1 cm long and 0.3 cm wide. The peak daily emergence of moths from pupae occurs from 7 a.m. to 3 p.m. (Lingren, 1983). Mating occurs in summer from 2 a.m. to 5 a.m. but often earlier in the day in cool weather (Lukefahr and Griffin, 1957; Lingren *et al*., 1989) and generally begins the second night of adult life (Henneberry and Leal, 1979). The adults live 2–3 weeks and the females lay 100–200 eggs. The eggs are deposited singly or in small clutches (Fig. 1a) and hatch in 3–5 days. The larvae develop through four instars in 12–18 days, with a pupal stage of 6–8 days (Butler and Henneberry, 1976b). Moth emergence begins in late March and continues into late July and early August (Wene *et al*., 1961; Watson and Larsen, 1968; Watson *et al*., 1970; Rice and Reynolds, 1971; Slosser and Watson, 1972a; Sevacherian *et al*., 1977; Fye, 1979a). The eggs laid by these moths produce first generation larvae that enter cotton flower buds (squares) and mature about the time the cotton flowers open (Fig. 1b). Westphal *et al*. (1979) reported a higher shed of PBW-infested flower buds as compared with non-infested flower buds. The larvae spin webs that tie the tips of the flower petals together causing the characteristic 'rosetted blooms' (Fig. 1c) (Noble and Robertson, 1964). Butler and Henneberry (1976a) found that approximately 40% of the rosetted blooms did not produce mature bolls. The larvae exit the blooms and pupate in and on the soil and emerge as adults in 4–7 days. The subsequent generations develop primarily within the maturing fruit (Fig. 1d and e). As many as five generations may occur during the cotton-growing season in warmer areas of the southwestern United States (Slosser and Watson, 1972b). The PBW larval feeding activities stain and destroy lint and feeding on seed reduces lint production (Fig. 1f). The PBW overwinters as diapause last instar larvae in cotton bolls, ground litter or in the soil. Diapause is induced by a combination of low temperatures (<21.1 °C) and short day conditions (<13 h) (Adkisson *et al*., 1963; Gutierrez *et al*., 1981).

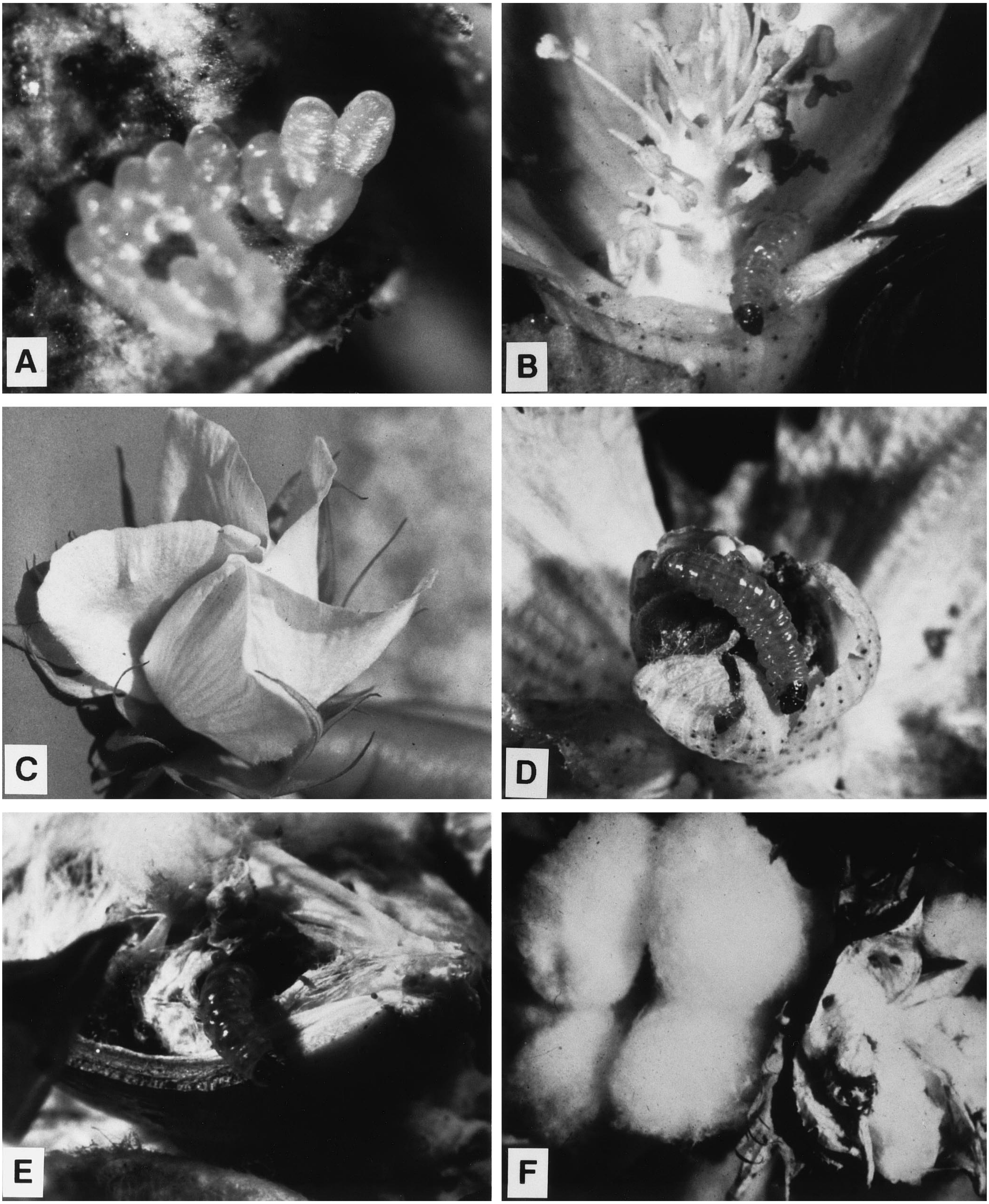


Fig. 1. PBW infestations in cotton. (A) Eggs laid beneath the boll caylx, (B) first generation larvae feeding in a cotton flower, (C) rosetted bloom caused by mature first generation larva webbing petals together before pupation, (D) and (E) larvae feeding on maturing cotton fruit and (F) comparison of undamaged (left) and PBW-damaged boll (right).

Table 1. Arthropod predators of *P. gossypiella* in the southwestern United States

Species	Type of study[a]	Stages attacked[b]	Reference
Araneida			
Metaphidippus californica (Peckman & Peckman)	Laboratory	L1 and L4	Orphanides *et al*. (1971)
Metaphidippus sp.	Laboratory	L1 and L4	Orphanides *et al*. (1971)
Trachelus sp.	Laboratory	L1 and L4	Orphanides *et al*. (1971)
Six unidentified species	Laboratory	L1 and L4	Orphanides *et al*. (1971)
Coleoptera			
Calosoma affine Chaudoir	Laboratory	L4	Orphanides *et al*. (1971)
Collops marginellus LeConte	Laboratory	E and L1	Orphanides *et al*. (1971)
C. vittatus (Say)	Laboratory	E	Fye (1979b) and Henneberry and Clayton (1985)
	Field gut assay	E	Hagler and Naranjo (1994a)
Hippodamia convergens Guerin-Meneville	Laboratory and field gut assay	E and L1	Orphanides *et al*. (1971) and Fye (1979b), Henneberry and Clayton (1985) and Hagler and Naranjo (1994a)
Notoxus calcaratus Horn	Laboratory and field cage	E and L1	Orphanides *et al*. (1971) and Irwin *et al*. (1974)
Dermaptera			
Labidura riparia (Pallas)	Laboratory	E, L1, L4, PP and P	Orphanides *et al*. (1971)
Hemiptera			
L. hesperus Knight	Field gut assay	E	Hagler and Naranjo (1994b)
Geocoris pallens (Stal)	Laboratory, field cage and field gut assay	E	Irwin *et al*. (1974) and Hagler and Naranjo (1994b)
Geocoris punctipes (Say)	Laboratory, field cage and field gut assay	E and L1	Orphanides *et al*. (1971), Irwin *et al*. (1974) and Hagler and Naranjo (1994b)
Nabis alternatus Parshley	Laboratory, field cage and field gut assay	E and L4	Irwin *et al*. (1974), Fye (1979b) and Hagler and Naranjo (1994b)
Nabis americoferus Carayon	Laboratory and field cage	E, L1, L4 and PP	Orphanides *et al*. (1971) and Irwin *et al*. (1974)
O. tristicolor (White)	Laboratory, field cage and field gut assay	E and L1	Orphanides *et al*. (1971), Irwin *et al*. (1974), Henneberry and Clayton (1985) and Hagler and Naranjo (1994b)
Sinea confusa Caudell	Laboratory and field gut assay	E and L4	Fye (1979b), Henneberry and Clayton (1985) and Hagler and Naranjo (1994b)
Sinea diadema (F.)	Laboratory	E, L1, L4 and PP	Orphanides *et al*. (1971)
Spanogonicus albofasciatus (Reuter)	Laboratory and field cage	E	Irwin *et al*. (1974)
Zelus renardii Kolenati	Laboratory and field gut assay	E, L1, L4, PP and P	Orphanides *et al*. (1971), Fye (1979b) and Hagler and Naranjo (1994b)
Neuroptera			
Chrysoperla carnea (Stephens)	Laboratory and field cage	E, L1 and PP	Orphanides *et al*. (1971), Irwin *et al*. (1974) and Henneberry and Clayton (1985)

[a]Laboratory, prey consumption/prey preference studies; field cage, prey consumption/preference measured in small cages in the field; field gut assay, serological assays conducted on field-collected predators.
[b]E, egg; L1, first stage larvae; L4, fourth stage larvae; PP, pre-pupae; P, pupae.

Plant hosts

Although plants of seven families, 24 genera and 70 species (43 species occur in the southwestern United States) have been recorded as PBW alternate hosts (Noble, 1969), okra, *Abelmoschus esculentus* (L.), is the only host other than cotton extensively cultivated in the United States. The contribution of weeds and other native vegetation to PBW population dynamics is not clearly known but is not considered a major factor influencing cotton infestations (Noble, 1969). The fact that the PBW is essentially limited to cotton in the United States is a major advantage for management approaches.

Natural mortality

Diapausing larvae are subjected to a number of adverse climatic and biological factors that result in mortalities of 48–99% (Slosser and Watson, 1972a; Fullerton *et al*., 1975; Bariola *et al*., 1976; Bariola, 1983). However, in most cases, survival occurs in sufficient numbers to develop economic levels of infestation the following year. The mechanisms involved which induce larval mortality in the soil, except for the physical impact of tillage and soil burial, are not known. However, fungi-infected larvae are occasionally observed (T.J. Henneberry, unpublished data) and numerous other soil microbes as well as arthropod predators could possibly be involved.

The reproductive capability of emerging moths from the overwintering generation and the survival of F_1 generation eggs and larvae are adversely affected by several biological and environmental factors. Moth emergence before cotton fruiting forms (3 days before cotton squaring; Bariola, 1978) are available as a source of larval food is termed suicidal (Chapman *et al*., 1960; Adkisson *et al*., 1962). Spring irrigations stimulate early emergence and can be timed to increase suicidal emergence (Beasley and Adams, 1995). Early in the season, the PBW larvae also are subject to extremely high soil temperatures prior to the development of the cotton plant canopy that provides shade. Larvae that develop in cotton squares exit flowers between 9 a.m. and 1 p.m. when the soil temperatures can be 60–66 °C (Butler and Henneberry, 1976a). High mortality often occurs (Fye, 1971; Clayton and Henneberry, 1982), with reduced reproduction of the surviving adults (Henneberry and Clayton, 1982a).

Natural enemies

The impact of indigenous natural enemies on PBW populations in cotton is not well understood. Quantifying and predicting the impact of natural enemies, as a group or as individuals, has been difficult because of the many species involved and because of the complex biological and ecological interactions occurring within and between natural enemies, as well as with their pest-insect hosts. Biological control efforts for the PBW in the western United States were recently reviewed by Naranjo *et al*. (1995).

Numerous arthropod predator species are found in Arizona and southern California cotton fields (Telford and Hopkins, 1957; Wene and Sheets, 1962; van den Bosch and Hagen, 1966) and many are capable of feeding on one or more stages of the PBW (Table 1). The egg and first instar larvae are most vulnerable to predation. The later stage larvae developing within fruiting forms are protected. Oviposition occurs on vegetative cotton plant parts until mid-July (Brazzel and Martin, 1957; Henneberry and Clayton, 1982c). During this period, the eggs and young larvae searching for suitable fruiting forms are exposed to high risks from predation. Later in the season, female moths oviposit under the calyx of green bolls and the eggs are protected, to some extent, from predators. Some of these eggs can be reached and destroyed by pedators (Orphanides *et al*., 1971; Irwin *et al*., 1974).

Henneberry and Clayton (1985) artificially placed PBW eggs on cotton terminals in the field through the season and found that predation ranged from 95% in July to 35% in September. Recently, a serological technique was developed in order to assay the gut contents of field-collected predators for the presence of PBW egg remains (Hagler *et al*., 1994). Serological analysis of nine of the more common predator species (see Table 2) revealed that *Collops vittatus* (Say), *Geocoris* spp., *Orius tristicolor* and *Lygus hesperus* were the most frequent predators of PBW eggs through the season. Based on predator population densities and simple assumptions about prey consumption rates, Naranjo and Hagler (1997) estimated that this complex of common predators was responsible for killing approximately 20% of all PBW eggs through the season. Although this level of predation clearly does not regulate populations it may be a valuable adjunct to other contemporaneous mortality factors.

Several native parasitoids have been reported attacking the PBW (Noble, 1969; Ferro and Rice, 1970; Jackson and Patana, 1980), the most notable being *Bracon platynotae* (Cushman). Some species can impose significant parasitism in localized areas and may provide PBW control in some instances (Jackson, 1980). Considerable effort has been made to import exotic parasitoids for classical biological control of the PBW. A total of 16 parasitoid species, representing four families and seven genera, have been released against the PBW in California and Arizona (Table 2). Although the survey work is somewhat incomplete, none of these species have apparently become permanently established in the southwestern United States (Legner and Medved, 1979; Gordh and Medved, 1986). A major impediment to the establishment of these exotics has been the widespread use of broad-spectrum insecticides (Bryan *et al*., 1973a; Legner and Medved, 1979). Several of these parasitoids are still in culture and it may be worthwhile reattempting introductions within an area-wide management framework that likely would greatly reduce the use of insecticides. Work continues on several promising parasitoids, such as *Trichogrammatoidea bactrae* Nagaraja, *Apanteles oeone* Nixon and *Chelonus* nr *curvimaculatus* Cameron, that may eventually be useful for PBW control (Hutchison *et al*., 1990; Naranjo *et al*., 1992a; Naranjo, 1993; Hentz *et al*., 1997).

The impact of natural mortality factors, the environment and natural enemies in early season has not been quantified. However, the PBW population increase per generation early in the season is slow (0.5–1.5 times) compared with late-season increases (2.4–15.0 times) (Graham *et al*., 1962; Slosser and Watson, 1972b; Bariola,

Table 2. Parasitic Hymenoptera released for biological control of *P. gossypiella* in the southwestern United States

	Origin	Stage attacked	Release locality	Year	Reference
Bethylidae					
Goniozus aethiops Evans	Ethiopia	Larva	California	N/A	Gordh and Evans (1976)
				1970–1973	Legner and Medved (1979)
Goniozus emigratus (Rohwer)	Hawaii	Larva	California	1970–1972	Legner and Medved (1979)
Goniozus pakmanus Gordh	Pakistan	Larva	Arizona	1984	Gordh and Medved (1986)
			California	1985	
Braconidae					
Apanteles angaleti Muesebeck	India	Larva	California	1970–1971	Legner and Medved (1979)
A. oenone Nixon	Australia	Larva	California	1975	Legner and Medved (1979)
Bracon gelechiae Ashmead	India	Larva	California	1969–1971	Legner and Medved (1979)
Bracon kirkpatricki (Wilkinson)	Mississippi	Larva	Arizona	1971	Bryan *et al*. (1973a)
				1972	Bryan *et al*. (1973b)
				1973	Bryan *et al*. (1976)
	Kenya		California	1969–1972 and 1975	Legner and Medved (1979)
Bracon mellitor Say	Mississippi	Larva	California	1972–1973	Legner and Medved (1979)
Chelonus blackburni Cameron	Hawaii	Egg–Larva	Arizona	1971	Bryan *et al*. (1973a)
				1972	Bryan *et al*. (1973b)
				1973	Bryan *et al*. (1976)
				1977–1978	Legner and Medved (1979)
				1978	Legner and Medved (1981)
			California	1970–1972	Legner and Medved (1979)
C. curvimaculatus Cameron	Kenya	Egg–Larva	California	1969	Legner and Medved (1979)
C. nr. *curvimaculatus* Cameron	Ethiopia	Egg–Larva	Arizona	1977–1978	Legner and Medved (1979)
				1978	Legner and Medved (1981)
			California	1973–1975	Legner and Medved (1979)
				1973 and 1975	Legner (1979)
C. nr. *curvimaculatus* Cameron	Ethiopia		California	1973–1975	Legner and Medved (1979)
				1973 and 1975	Legner (1979)
C. nr. *curvimaculatus* Cameron	Australia		Arizona	1977–1978	Legner and Medved (1979)
				1978	Legner and Medved (1981)
			California	1976	Legner and Medved (1979)
Ichneumonidae					
Exeristes roborator (Fabricius)	Yugoslavia	Larva	California	1971–1973	Legner and Medved (1979)
Pristomerus hawaiiensis Ashmead	Hawaii	Larva	Arizona	1977	Legner and Medved (1979)
			California	1970–1975	
				1974	Legner (1979)
Trichogrammatidae					
T. bactrae Nagaraja	Australia	Egg	California	1986–	G. Gordh (unpublished), Hutchison *et al*. (1990) and Naranjo *et al*. (1992a,b)

1978). Supplemental management strategies designed to exploit low-level, early-season population increases are particularly desirable. This vulnerable period provides an opportunity for additional, environmentally acceptable control methods.

Augmentative releases of *T. bactrae* wasps, an egg parasitoid of the PBW imported into the United States from Australia in 1985, have shown some promise for early-season control in Arizona (Naranjo *et al*., 1992a). In small-scale replicated plots, weekly releases of this parasitoid significantly reduced boll infestations during July in comparison with control plots. Parasitoid releases also increased the yield by 10–13% and reduced seed damage by 22–56%. The parasitoid is well adapted to the high temperature conditions of the southwestern United States (Naranjo, 1993), readily attacks the eggs of other pest lepidoptera in cotton (Hutchison *et al*., 1990; Naranjo *et al*., 1992b) and is currently available from several commercial insectaries. The potential for PBW control by *T. bactrae* is best in the early season when PBW eggs are deposited mainly on vegetative plant surfaces. The results indicate that the parasitoid only attacks 7–15% of the eggs laid under the calyx later in the season, a level insufficient for pest control (Naranjo *et al*., 1992a).

Entomopathogenic nematodes appear to have potential application in PBW management (Lindegren *et al*., 1993a; Henneberry *et al*., 1995a,b, 1996). PBW larvae are highly susceptible to *Steinernema carpocapsae* (Weiser) and *Steinernema riobravis* Cabanillas, Poinar and Raulston (Lindegren *et al*., 1992, 1993b, 1994; Henneberry *et al*., 1995a,b, 1996). Entomopathogenic nematodes, as soil inhabitants, escape insecticide exposure, except for soil-applied systemics. *Steinernema riobravis* has better host searching efficacy than *S. carpocapsae* (Lindegren *et al*., 1993a) and is more tolerant of high temperatures (Henneberry *et al*., 1996), a highly desirable characteristic under desert growing conditions. Treatment of commercial cotton fields in Arizona (2.5 billion nematodes ha^{-1}) showed that *S. riobravis* persisted in large numbers for 19 days and were recovered up to 75 days following treatment (Gouge *et al*., 1996). The numbers of cotton bolls infested by the PBW during the season were reduced and the cotton yield increased 19% compared with untreated cotton fields. Similar results were obtained with *S. riobravis* in cotton fields at the Texas A & M Agricultural Research Center, El Paso, Texas. The timing of application and the application methods and application rates are being refined in further research, but the implementation of entomopathogenic nematodes in area-wide management programmes appears promising.

Models

Several models, from very simple to very detailed, have been developed to aid PBW management efforts. Several simple degree-day models for forecasting spring emergence patterns have been developed (e.g. Sevacherian *et al*., 1977; Huber *et al*., 1979). Recently, Beasley and Adams (1996) used field data to determine the optimal lower and upper threshold temperatures and the accumulation starting dates for predicting the spring emergence and for estimating the generational peaks over the growing season. Along with weather forecasts, such models permit growers to time control activities better and make best use of tactics such as delayed planting to maximize the avoidance of emerging moths (see the section on early-season management below). Gutierrez *et al*. (1977) coupled a physiologically based cotton plant model to a temperature-dependent PBW model to examine the impact of weather on insect–plant interactions. The results provided insight into the potential for PBW population development in the San Joaquin Valley. The insect model was later modified by Stone and Gutierrez (1986a,b) to reflect more accurately the effect of the fruit age on the PBW biology and to incorporate the effects of insecticide and pheromone applications on pest control. Simulation was used to construct hypotheses concerning the comparative profitability of various pest control strategies based on the use of insecticide or pheromone alone or in combination (Stone and Gutierrez 1986a,b; Stone *et al*., 1986). Unfortunately, these hypotheses have not been widely tested in the field. Although such complex models require a large number of inputs, they have been useful in IPM for describing crop and PBW phenology and development and for predicting events that influence decision making in pest/crop management. Perhaps the most important use of such models in pest management is that they provide a means to structure the existing knowledge of the pest–crop system and, by comparing simulations to field observations, they help to identify areas where our understanding is deficient (Gutierrez *et al*., 1980). This approach will be an essential component of PBW area-wide population suppression.

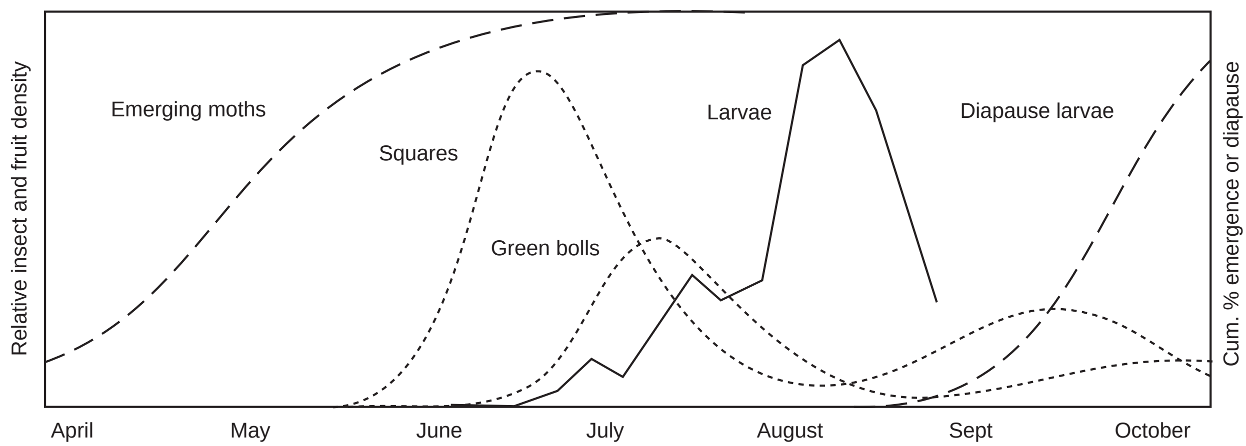
Current management options and approaches

Cotton crop production

Cotton grown in the southwestern United States may remain in the ground for more than 10 months (Willet *et al*., 1973). The planting dates range from late March to early May depending on elevation and latitude. Typically, cotton begins to set bolls during the first fruiting cycle in early June. The peak boll set occurs in early to mid-July. The second fruiting cycle in full-season production systems begins in late July and early August continuing until cool weather slows plant growth. Over 90% of the total crop production for upland cottons is produced by 15 September. Cotton bolls formed after 1 September may not mature and the lint quality is generally lower than for lint produced in the first fruiting cycle. These are important considerations in PBW management during the early, mid- and late season portions of the production cycles, as well as following crop harvest (Graham, 1980). The selection and implementation of compatible methods must be in accord with the crop production methods to obtain grower and agricultural community acceptance. The array of tactics available during these portions of the crop cycle form the foundation for an area-wide management system (Fig. 2). In the authors' view, preference should be given to cultural, biological and behavioural approaches rather than chemicals.

Early-season management

Heat units for predicting pest and crop phenology. Degree-day summation can be effectively used to project the emergence of overwintering PBW moths and the availability of suitable host material for pest reproduction (Gutierrez *et al*., 1977; Sevacherian *et al*., 1977; Huber *et al*., 1979; Beasley and Adams, 1996). These temperature-based forecasts are important for pinpointing the times to begin pheromone-trap sampling and plant observations to validate the occurrence of fruiting cotton, which in turn can identify potential problem areas. Calendar date estimates are highly variable because of the temperature-dependent PBW development and cotton plant growth.



Early-Season

Natural Mortality
Natural Enemies
Planting Date
Heat Units
Plant Phenology
Host Plant Resistance
(transgenic cotton)
Mating Disruption (pheromone)
Sampling (pheromone traps)
Models
Augmentative Biocontrol?
Chemical Control (pin-head)
Resistance Management
Sterile Insect Release
Crop rotation
Irrigation Timing (stimulate emergence)

Mid-Season

Natural Enemies?
Heat Units
Plant Phenology
Host Plant Resistance
(transgenic cotton)
Mating Disruption (pheromone)
Sampling (pheromone traps)
Sampling (green bolls)
Models
Augmentative Biocontrol?
Chemical Control
Resistance Management
Sterile Insect Release

Late-Season

Natural Enemies?
Heat Units
Plant Phenology
Host Plant Resistance
(transgenic cotton)
Sampling (pheromone traps)
Sampling (green bolls)
Models
Augmentative Biocontrol?
Chemical Control
Resistance Management
Plant Growth Regulators
Irrigation Cutoff
Defoliation
Sterile Insect Release

Post-season

Natural Mortality
Stalk Cutting/Shredding
Plough down Date
Winter Irrigation

Fig. 2. Summary of PBW and cotton crop dynamics over the growing season and available control tactics for pest population suppression over specific portions of the season.

Pheromone traps. Gossyplure-baited traps have proved to be highly effective for the early-season detection and population monitoring of moth populations (Fig. 3) (Beasley *et al*., 1985). The relative magnitude and time of occurrence of pheromone-baited trap catches of the early-season PBW indicate moth emergence from overwintering populations that initiate infestations in the current year's crop. The numbers of male moths caught 3–4 days prior to the first squaring of cotton are positively correlated to the flower infestations during the first fruiting cycle (Beasley *et al*., 1985). In turn, the numbers of PBW larvae in bolls during the first fruiting cycle are positively correlated to the flower and boll infestations during the second fruiting cycle. Therefore, careful monitoring of pheromone traps and early-season flower infestations can provide useful information for estimating the extent and magnitude of the moth population that will subsequently oviposit and produce economic infestations of larvae in bolls.

Planting date. Approximately 95% of PBW moths emerge from overwintering during mid-March through to mid-June. Cotton squares are present in Arizona and southern California cotton between mid-May and early June for cotton planted between 20 March and 20 April. Under these conditions, the suicidal emergence can range from 57 to 86% (Wene *et al*., 1961; Watson and Larsen, 1968; Watson *et al*., 1970; Rice and Reynolds, 1971; Slosser and Watson, 1972a; Bariola, 1978). Delayed planting can prolong the period of suicidal emergence (Adkisson *et al*., 1962; Henneberry *et al*., 1982), but may not be practical in all areas. However, it may be a useful management tool in areas where good plant stands can be established later in the season and effective additional methods are employed to protect late-season bolls. Uniform planting dates must be accepted by all growers in a management area to avoid variability in the plant phenology and different stages of cotton fruiting development (Henneberry *et al*., 1982).

Using the concept of a planting date window, researchers in Arizona have devised a system that attempts to maximize the suicidal emergence period of adult PBW moths while maintaining planting dates that optimize the yields of full-season cultivars (Brown *et al*., 1992). The system uses a degree-day scale to balance the timing of 75% suicidal emergence against the first occurrence of fruiting forms suitable for PBW reproduction (Fig. 4). The upper bound of the window surrounding this 'optimal' planting date is set to conform to the known performance characteristics of full-season cultivars grown under Arizona conditions. The concept is simple and is enhanced by the availability of real-time local weather data and advisories issued by the cooperative extension service.

Cultivar resistance. The use of genetic characteristics in plants that render them less susceptible to attack from insect pests is one of the most economical and acceptable methods of pest population suppression. Although PBW resistances to cottons based on their nectariless character have been identified and incorporated into acceptable agronomic types (Lukefahr and Griffin, 1956; Lukefahr *et al*., 1965; Wilson and Wilson, 1976), they have not been utilized extensively. A nectariless, early-maturing, okra leaf cotton germplasm line was developed by Wilson *et al*. (1991). The cotton yielded 12% more lint, was significantly earlier in maturing and required only 59% as much insecticide for PBW control compared with a standard cotton cultivar. Resistance appears to result from reduced oviposition on the bolls and reduced penetration of the bolls by neonate larvae (Wilson *et al*., 1986; Flint *et al*., 1991; Naranjo and Martin, 1993). Natural enemies are known to feed on extra-floral nectaries (e.g. Yokoyama, 1978) and numerous studies have documented decreases in natural enemy populations in nectariless cotton (see the reviews by Bergman and Tingey (1979), Schuster and Calderon (1986) and Naranjo and Gibson (1996). Given the overall paucity of knowledge on natural enemy effects (see above) it is difficult to assess the potential effects of nectariless cotton on natural pest control; however, such interactions should not be ignored.

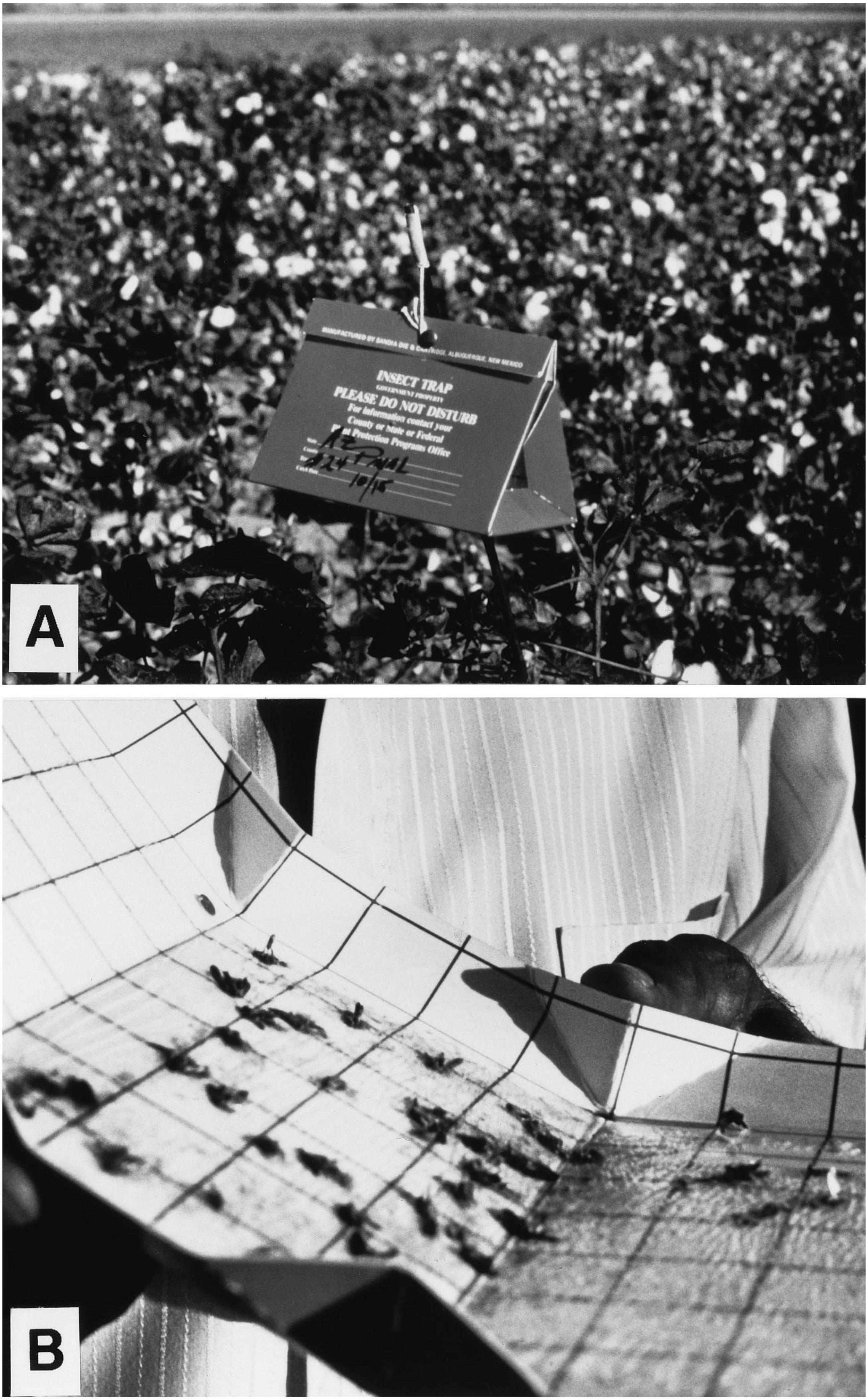
The potential for developing other resistant PBW cottons is high since 45 cotton lines and cultivars have been identified that show some level of resistance (Wilson, 1982). Several short-season, early-maturing cotton lines, developed throughout the United States cotton belt and grown under southern California conditions, escaped the late-season PBW and produced acceptable yields (Walhood *et al*., 1981, 1983). Economic analyses have shown that it is feasible to use short-season cultivars in Imperial Valley, California (Burrows *et al*., 1982). They have not, however, become accepted by growers.

Transgenic cotton lines and cultivars carrying the gene to produce *Bacillus thuringiensis* (BT) vr. kurstaki (Berliner) endotoxin have a high degree of PBW resistance and have been developed commercially (Wilson *et al*., 1992, 1994). PBW infestations in Bollgard™ (Monsanto Company, St Louis, Missouri) Deltapine-50 cotton were reduced 93–99% and nearly 100% in 2 years of testing compared with non-transgenic DPL-50 and Coker 312 cultivars (Flint *et al*., 1995). In commercial fields, NuCoTN 33 (Delta and Pineland Company, Scott, Mississippi) has provided nearly complete control of the PBW (Flint *et al*., 1996). These cottons are gaining increased acceptance in the agricultural communities of the southwest where the PBW is a problem. The long-term impact of transgenic cultivars on PBW populations is speculative. The management of BT transgenic cultivars to avoid the development of resistance in the PBW and other lepidoptera is of concern and is the subject of much current research. Because transgenic cottons are relatively new in the United States, their effects on other pests and beneficial species have not been widely studied. Much work is currently under way in this area as well.

Behavioural control. The PBW sex pheromone was identified in 1973 as a 1:1 ratio of the *Z,Z*- and *Z,E*-isomers of 7,11-hexadecadienyl acetate and named 'gossyplure' (Hummel *et al*., 1973). Behavioural control with gossyplure is based on the concept that permeation of the material into the atmosphere of cotton fields results in the disruption of moth communication, the inhibition of male moth orientation and the prevention or reduction of mating. The potential of gossyplure for PBW behavioural control was demonstrated by Shorey (1976) and Gaston *et al*. (1977).

The application of commercially developed, controlled-release gossyplure carrier systems (Brooks and Kitterman, 1977; Brooks *et al*., 1979; Doane and Brooks, 1981; Kydonieus and Beroza, 1981) showed reduced boll infestations and female mating under low population density in grower fields (Henneberry *et al*., 1981; Butler *et al*., 1983). The addition of pyrethroid insecticide to the adhesive sticker used with a hollow-fibre, slow-release gossyplure system has, with various modifications, also been used commercially (Staten and Haworth, 1981). The most recent development in gossyplure slow-release formulations is the PBW-ROPE® (Shin-Etsu Chemical Industry Co., Ltd, Tokyo, Japan). Promising research results (Flint *et al*., 1985) led to large-scale demonstration trials under low PBW population densities in the Imperial and Coachella Valleys in California and Mexicali Valley, Mexico (Staten *et al*., 1987a,b). Insecticide use was significantly reduced in PBW-ROPE®-treated fields as compared with fields under conventional insecticide control practices. The boll infestations were comparable in both systems, but were significantly less in PBW-ROPE®-treated fields as compared with fields treated with conventional insecticides at one location. Other behavioural control possibilities exist using only one or different ratios of the two component isomers of gossyplure (Flint and Merkle, 1983).

Chemical control. Early-season insecticide applications for PBW control should, in general, be avoided in order to preserve natural enemy populations and reduce secondary pest outbreaks. However, the selective placement of organophosphate insecticides (directed sprays, four applica-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tions at 6 day intervals) to cotton in the seven- to eight-leaf stage of development have been shown to delay the establishment of PBW infestations and increase yields (Tollefson, 1987). The practice has been adopted by some Arizona cotton growers. The important aspects of the approach appear to be a reduced need for chemical control later in the season and the recovery of natural enemy populations that prevent secondary pests as demonstrated for the bollweevil, *Anthonomus grandis* Boheman (Taft and Hopkins, 1963; Heilman *et al*., 1977). Early-season control with insecticides must be carefully weighed against the possibility of encouraging outbreaks of secondary pests.

Mid-season management

Sampling and chemical control. Damaging infestations of the PBW rarely occur before late July to early August. Control efforts may be necessary to prevent economic losses; however, sizeable initial infestations can be tolerated without reduced cotton yields (Watson and Fullerton, 1969). At least 20% of the firm green bolls can be infested with larvae in early season before control measures are warranted (Watson and Fullerton, 1969). The common practice is to initiate treatments when 5–10% of the bolls are infested with larvae (Ellsworth *et al*., 1994). Boll sampling should be initiated as soon as susceptible (14–21 days old) bolls are available. The PBW moth density, as measured in pheromone-baited traps, provides good supplemental data (Toscano and Sevacherian, 1980). When susceptible cotton bolls are first available in large numbers (June through to July), catches of 12–15 male moths per pheromone trap per night indicate the need to initiate control action, but do not eliminate the necessity for boll sampling (Toscano *et al*., 1979). Trap catch data thereafter are more difficult to interpret, because the numbers of moths caught are not reduced or reduced for only 1–2 days following insecticide application, even though the insecticides may be effectively reducing the boll infestations (Henneberry and Clayton, 1982b). This may occur because of continuing emergence in the fields, between-field movement of the moths or sublethal effects of the chemicals on adult moths. In any event, the management of PBW populations with chemicals during the peak availability of susceptible cotton bolls must be accompanied by an estimation of the boll infestations on a field by field basis.

Maximum numbers of PBW-susceptible bolls occur approximately 3 weeks after peak flowering (Fry and Henneberry, 1983). After peak flowering (boll set) fewer susceptible bolls are available and higher PBW levels may occur but have less effect on the total yield. The timing of applications is particularly critical, since insecticide control effectiveness is based on killing adult moths (Reynolds, 1980). When susceptible bolls are available, eggs are laid under the calyx or on bracts and are relatively inaccessible to insecticide deposits. Larvae enter the boll soon after hatching from the eggs and are not killed by insecticides when they are within the boll. Sampling for bolls infested with eggs instead of larvae can reduce insecticide use by 28–35% without any significant loss of yield or lint quality (Hutchison *et al*., 1988, 1991). However, eggs are much more difficult to see in the field and the technique has not been widely adopted as a method for sampling and decision making in PBW management.

Fig. 3. Phermone trap for monitoring the abundance of PBW male moths in the field. (A) Typical placement of trap within the crop canopy and (B) capture of male moths.

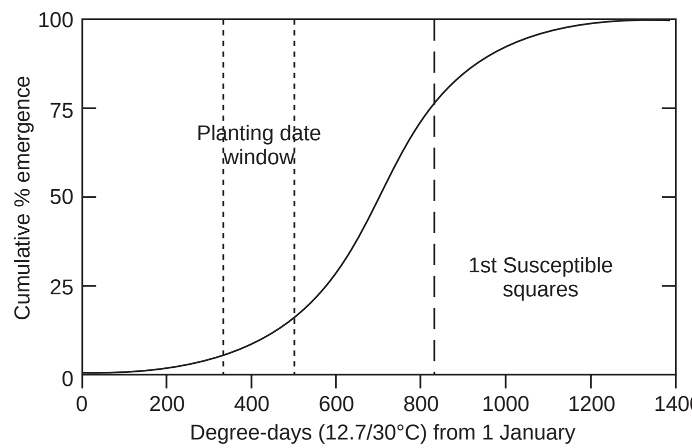

Fig. 4. Diagram of Arizona plant date system that attempts to balance acceptable yields with maximal levels of suicidal emergence of PBW in the spring. The concept is based on susceptible hosts first becoming available 500 degree-days (°C) after planting.

Insecticide resistance management. PBW resistance to chlorinated hydrocarbons was reported in Mexico and Texas in the 1950s and 1960s (Lowry and Berger, 1965) and tolerance to certain synthetic pyrethroid compounds has occurred more recently (Haynes *et al*., 1986, 1987). These reports are of particular concern because documented entomological experiences over the years have shown that once resistance to a given compound occurs in a population, it develops more rapidly to other types of insecticides. The only feasible method to prolong the life of the currently available insecticides is to reduce the selection pressure that results in the development of resistant strains. Therefore, in PBW pest management systems where insecticides must be used, it is necessary (1) to incorporate insecticide resistance monitoring and rotating insecticides with different modes of action to reduce or avoid resistance development (Haynes *et al*., 1986, 1987) and (2) to encourage cultural and other available non-chemical control technologies to reduce PBW populations.

Late-season management

Reduction of the diapause generation. Diapause larvae may occur as early as late August, but their incidence is low until mid-September. Thereafter, the percentage of diapause larvae increases to 50% or more by 1 October and 80% by mid-October (Henneberry, 1986). Insecticide applications are generally terminated in mid- to late September because of the high treatment costs and reduced benefits in the potential yield. High larval populations that occur in late-season bolls represent the overwintering diapause generation. Typically, 90% of the total upland cotton bolls produced are set by 15 September. Bolls set after late August to mid-September may not mature or may produce fibre of low quality (Bennett *et al*., 1967). However, under southwestern growing conditions, immature bolls may be produced until frost. Thus, high percentages of the diapausing PBW larvae develop in bolls that may not contribute significantly to the yield, but do provide a source of PBW for infesting cotton planted the following year. In most instances, over 95% of the diapausing larval generation develops in bolls after 15 September.

Crop management objectives that minimize yield losses while reducing overwintering PBW populations are essential components of pest management in southwestern, full-season production systems. This may be accomplished by limiting the availability of the host material after mid-September to prevent diapause larval population development. Inducing a high mortality of diapause larvae is a second choice accomplished through intensive tillage and crop residue plough down.

Plant growth regulator treatments have been developed that effectively remove late-season fruiting forms. These materials limit the development of the diapause PBW generation by eliminating host material in late season without affecting the cotton yields. The method was suggested by Kittock *et al*. (1973) and demonstrated to have potential by Bariola *et al*. (1976). At present, ethephon and thidiazuron are registered as harvest aid chemicals to accelerate mature boll opening and defoliate cotton, respectively. Applications of ethephon or thidiazuron in early September were shown to reduce the number of green bolls at harvest time and reduce the number of diapausing PBW larvae (Bariola *et al*., 1987). The acceleration of mature boll opening by ethephon makes it possible to harvest earlier, shred stalks and plough down crop residues. These are very effective cultural practices in PBW population suppression (Henneberry *et al*., 1988).

Early cotton crop termination by water management to shorten the growing season and reduce the amount of late-season host material is another approach (Watson *et al*., 1978). The cotton growth and fruiting decreases slowly as the soil dries out. Thus, terminating irrigation early and using plant growth regulators as discussed above can be good complementary practices.

Post-season management

Cultural. The destruction of PBW diapause larvae in their overwintering habitat by combined mechanical and cultural means is the most effective management tool for PBW population suppression. Stalk shredding to enhance uniform and deep burial of shredded plant debris, followed by discing, ploughing and winter irrigation treatments, effectively reduces the number of overwintering pink bollworms (Watson, 1980). The most effective, practical tillage practice has been deep ploughing that results in turning over the soil to a depth of 15 cm as soon as possible after harvest. Early crop plough down increases the larval mortality and reduces spring moth emergence. Discing and winter irrigation alone can also induce significant winter mortality (Watson, 1980).

Large-scale demonstration trials

Some of the control tactics discussed have been implemented in cotton-growing communities with highly successful results.

Scouting and action thresholds

IPM systems in Arizona cotton began with the development of efficient cotton scouting programmes in the Safford Valley, to determine the need for insect control in lieu of scheduled insecticides (L. Moore *et al*., unpublished report). For the 3 years following the initiation of scouting programmes, the insecticide treatments were reduced 93, 96 and 82%, respectively (Carruth and Moore, 1973) and the costs of treatment per acre prior to scouting were \$15.00 as compared to \$2.70, \$2.54 and \$5.00 for the 3 years following the scouting programme implementation. Economic evaluation of other Arizona scouting programmes showed reductions of \$10.58 (Lawrance, 1972) and \$13.66 per acre (Olmstead, 1976) for pest control by growers implementing IPM practices as compared to conventional calendars scheduling of insecticide applications.

Pheromone application

Behavioural control with gossyplure as the primary IPM component was used in an isolated 11 340 ha of cotton near Parker, Arizona. The male moth populations were reduced (gossyplure-baited trap catches) 71, 87 and 96%, respectively during years, 1, 2 and 3 following initiation of the programme (El-Lissy *et al*., 1993). The larval populations in bolls were reduced 93, 96 and 100%, respectively.

Sterile insect releases

Sterile moth releases were initiated in 1968 as the principle IPM component in San Joaquin Valley, California (Henneberry, 1994). The objective was to prevent the establishment of PBW infestations in the area from migrating moths from infested areas to the south. The programme currently involves (1) PBW gossyplure-baited traps to detect native migrant moths and to indicate areas of needed suppressive action as well as to establish ratios of released sterile to native male moths in the field, (2) the release of radiation-sterilized moths, (3) cotton plant destruction and plough down to maintain a 90 day host-free period and (4) the mating inhibition and/or male annihilation technique involving field application of gossyplure slow-release systems (Foote, 1988). Native male moths have been trapped in the valley each year of the programme since 1969 and larvae found in bolls in several of those years. Diapausing PBW larvae have been demonstrated to survive, pupate and emerge in the spring in the area (A.C. Bartlett, personal communication). Indirect evidence suggests that the programme has successfully excluded established infestations from occurring.

Variable results have occurred with sterile PBW moth releases for suppressing established populations (Bariola *et al.*, 1973a; US Department of Agriculture, Animal and Plant Health Inspection Service, 1977). Failures have been attributed to low, ineffective sterile to native moth overflooding ratios. In contrast, sterile releases in the Moapa Valley, Nevada, resulted in a reduction of fertile progeny and decreases in the moth populations in release versus non-release fields (R. Staten, J.R. Brazzel, A.C. Bartlett and G.D. Robison, unpublished report). Under isolated conditions on St Croix, US Virgin Islands, the suppression of larval infestations in bolls required high ratios (⩾72:1) of released sterile to native moths (Henneberry and Keaveny, 1985). The high costs, complexity of the programme and need for an independent organizational structure to maintain and implement a sterile moth release programme suggests that some of the more readily implemented methods discussed in this review would be better choices for IPM. This is particularly true under high PBW population density conditions where cultural, chemical, biological and resistant cultivars will be essential in reducing populations to low levels before sterile releases can even be considered.

Cultural control

The impact of shortening the growing season using cultural control and plant growth regulators was demonstrated in the Imperial Valley, California. The earliest planting date was established as 1 March, 1 September as the date for defoliant or plant growth regulator application and 1 November as the date for cotton stalk destruction and plough down (Chu *et al.*, 1996). The male PBW trap catches were substantially reduced each year for the 4 years following the initiation of the programme. Fewer larvae per boll occurred during each season and the production of diapause larvae was reduced over 90%. The cotton yields and quality increased and the need for insecticidal control of the PBW decreased.

Multicomponent programme

Beginning in 1991, the growers in the farming communities northwest and west of Tucson, Arizona formed a grower task force to address the PBW problem which was extremely severe during the 1990 growing season. With the help of cooperative extension from the University of Arizona, a coordinated, multicomponent programme was put in place for controlling the PBW (Thacker *et al.*, 1994). The basic strategy of the 5200 ha area programme was to implement uniform planting dates timed to maximize suicidal PBW emergence, early planting of small acreages of cotton to act as a trap crop, the timely application of insecticides at the pinhead square stage of crop development, mid- and late-season scouting and the timely termination of the crop to minimize the size of the overwintering PBW population. The typical cost of the programme was approximately $32 ha^{-1} and it has been well received by participating growers.

Considerations for PBW area-wide IPM

General

More than 80 years of PBW research in the United States has resulted in a vast information base on biology and control. Much of this has been briefly reviewed in the foregoing sections. Programmes bringing together all or a large number of the available and appropriate methodologies for PBW population management have not been implemented to date. The likely causes are funding restrictions, logistics and the need for the cooperative efforts of scientists, growers, the public and the agricultural community. The terminology of ‘area-wide suppression’ of key pests was widely used in the 1970s and 1980s (Kogan, 1995). Ridgway and Lloyd (1983) suggested that total population management and IPM be merged as area-wide population management. Area-wide pest management can be identified as a combination of appropriate and compatible pest management tactics implemented at an ecosystem level that includes the pest and significant production areas of the animal or crop to be protected. The selected control methods observe the integrated management concepts of monitoring, the maximization of natural mortality, the conservation of natural enemy populations and the use of additional methods prescribed by established thresholds and economic feasibility. The involvement of extensive geographic areas affords the potential for applying the methods to all or most of the key pest populations and, thus, increases the probability that overall key pest infestations will not exceed levels that require remedial control action.

Area-wide programme initiative

In 1993 the Agricultural Research Service (ARS) of the United States Department of Agriculture (USDA) initiated discussions with the USDA Integrated Pest Management Working Group to develop a framework for collaborative activities on area-wide pest management (R.M. Faust, personal communication). The first organizational meeting was held on 27 September 1993 at Beltsville, Maryland and involved representatives from the USDA, university research and extension programmes and state departments of agriculture. This initiative stimulated expanding interest in area-wide pest management. A tentative list was made of a number of candidate key pests for area-wide management approaches. From this list the codling moth (*Cydia pomonella* (L.)) and corn rootworm complex (*Diabrotica virgifera virgifera* LeConte and *Diabrotica barberi* Smith and Lawrence) were selected as candidates. The codling moth and corn rootworm programmes were initiated in 1995 and 1996, respectively.

PBW characteristics favouring an area-wide management approach

The main area-wide management component for the codling moth programme is pheromone behavioural control resulting in mating disruption. Kogan (1995) suggested that the codling moth host specificity, moderate dispersal tendencies and relatively few generations per year coupled with the availability of a highly effective suppression technology (mating disruption) that reduced the probability of secondary pests (mites on apples and pear psylla and *Cacopsylla pyricola* Foerster on pears) associated with current insecticidal control were ideal characteristics favouring its selection as the prototype insect for area-wide management.

A comparison of the codling moth and PBW reveals some similarities and dissimilarities relative to these 'ideal' characteristics. Cotton is the preferred PBW host and the only one of consequence in United States cotton production areas where the PBW occurs. Okra is the only other host extensively cultivated in the United States. It is produced in limited quantities in the west and rarely in cotton production areas.

In contrast to the codling moth, the PBW has been documented to disperse long distances, apparently aided by winds and other weather factors (see below). Although PBW moths move within and between cotton fields during the season, the peak flight activity occurs in early season by overwintered moths and late in the autumn when the population densities are high and the crop is senescing (Van Steenwyk *et al*., 1978). Area-wide approaches that recognize these dispersal characteristics may largely ameliorate this migration effect by the isolation and/or implementation of suppressive tactics over a large geographical area.

The codling moth has one to three generations per year (Kogan, 1995). In contrast, the PBW has five or more generations per cotton-growing season over most of its range in southwest cotton production areas (Henneberry, 1986). The greatest increases in population growth occur in the third and fourth generations with little or no population increase during the first generation and a general decline in population growth in the fifth and later generations. Thus, control methods that negatively impact upon the establishment and development of the first generation and prevent or reduce population development in the fifth generation are highly desirable because they exploit the most vulnerable periods in the PBW life cycle. PBW management with biological and cultural tactics that avoid the disruptive effects of insecticides would have a major impact on the reduction of secondary pest problems. The variety of available and potential, non-insecticidal control approaches is perhaps the most significant feature in support of area-wide management for the PBW and is a feature not shared with the codling moth.

Site selection

The delineation of the boundaries, size and isolation of management areas are major issues for PBW area-wide programmes. The significant role of PBW moth migration in the spread and establishment of cotton infestations has been demonstrated by the failure of cotton-free zone restrictions, early eradication attempts and the development of infestations in isolated cotton fields as far as 120 km from infested areas (Ohlendorf, 1926; Coad, 1929; McDonald and Loftin, 1935). Moths have been collected up to altitudes of 900 m (Glick, 1939, 1957). The PBW dispersal potential under Arizona–California desert conditions has been demonstrated by several investigators (Bariola *et al*., 1973b; Graham, 1978; Stern, 1979; Beasley *et al*., 1985). Native PBW moths have been captured in the uninfested San Joaquin Valley, California, in pheromone-baited traps each year since 1968 (Animal and Plant Health Inspection Service, unpublished reports). These are strongly suspected as being migrants from southern desert valley, cotton-growing areas as much as 640 km distant. Wind trajectory analysis showed that southern California wind flows could result in the transport of PBW moths from the southern desert agricultural areas of the Coachella and Imperial Valleys to the central California San Joaquin Valley (Kauper, 1977).

PBW area-wide management may extend across county, state and national boundaries. Thus, in addition to the technical complexities of suppression, a high degree of local, state, national and international cooperation will be essential in assuring a high probability of success. The interaction of biotic and abiotic factors influencing the PBW and other components of the ecosystem become more complex as the boundaries of the management unit become larger and involve more diverse biological, agricultural and environmental components.

Isolation

PBW area-wide management units may be delineated by natural factors, such as the climate or geographical barriers, such as large bodies of water, desert, mountain ranges and/or host distribution. Other options also may exist. For example, the barrier zone concept established as one of the most important factors contributing to the success of the southeastern sterile insect release programme for eradication of the screwworm, *Cochliomyea hominivoras* (Coquerel) (Baumhover 1966) may be applicable in PBW programmes. Sterile screwworm flies were released in a buffer zone to prevent immigrants from establishing infestations inside the core eradication area. Similarly, a buffer zone was established using insecticides in early bollweevil eradication efforts to avoid infestations by bollweevils immigrating into management areas (Lloyd, 1972; Boyd, 1976; Ganyard *et al*., 1981). Other artificial barrier systems, such as the use of insect pheromones, sterile insect releases and/or other biological systems, may also have potential to prevent PBW movement into management areas (Lingren *et al*., 1977). The need for technology to isolate or delineate an area-wide pest management area may not always exist. Phillips and Nicholson (1979) and Phillips *et al*. (1981) reported that bollworm, *Helicoverpa zea* (Boddie), immigration was not a major factor contributing to outbreaks of the insect in a highly successful community participation pest management programme in Arkansas.

Suppression strategies

The components of a PBW area-wide management programme must be carefully selected to assure overall compatibility. Chemical, biological, genetic and cultural control methods, as well as the development and use of resistant cottons, is advancing rapidly. All control methods must be considered in PBW area-wide management. No single method is likely to be totally acceptable and combinations of two or more methods offer the highest probability of success. The control methods selected must consider how each method functions individually and simultaneously with each other to achieve population reduction.

Because of the broad geographical areas involved in cotton production in the southwestern United States and the adjacent cotton production areas along the border of northern Mexico, many different environmental, agricultural and social communities are involved. PBW population densities vary considerably between areas, moth dispersal over hundreds of miles has been demonstrated and the cotton production practices and cotton cultivars grown vary considerably. These factors combined suggest that a single, standard PBW management programme type will not be applicable to all growing areas. All management tactics will not be needed in every production area. Rather, the selection of methods to tailor-make management programmes for specific cotton production areas may be the most viable option. The identification of tactics that are compatible and implementable will require expertise from many areas of the agricultural community. Crop scientists and entomologists working with cooperative extension, growers, pest control advisers, state departments of agriculture, the agricultural chemical industry and cotton commodity support groups must work together in all stages of planning, implementation and assessment.

Agricultural community participation and benefits

University cooperative extension/education inputs in area-wide pest management are crucial to a successful programme. Extension services have extensive urban, grower community, research community, industry and support group contacts through training, workshops and computer networking. Open lines of communication to the public, the agricultural community and to industry that lead to an understanding of the strategies and goals of area-wide pest suppression will greatly facilitate programme support, participation, operation and efficiency. Technology transfer is also essential in the form of recommendations of implementable tactics that are tailor-made for different cotton production systems. Further, all members of the community have vital roles in the assessment of the programme impact. Reduced insecticide use, reduced costs, maintained or higher yields and quality and improved farm-community environments are the projected benefits. For example, an analysis of the performance of cotton boll-worm management communities in Arkansas showed that communities participating in the management programme experienced increased cotton yields (\$56.81 ha^{-1}), reduced insect control costs (\$4.57 ha^{-1}) and increased net returns (\$15.87 ha^{-1}) compared to communities not participating in management programmes (Parvin *et al*., 1984). Overall, the producers' incomes in the participating management communities were increased by \$1.5 million dollars and insecticide use was reduced by 41 768 kg of active ingredient (Cochran *et al*., 1985). Other benefits also occurred. Scott *et al*. (1983) analysed the effect of participation in the boll-worm management programme on other university cooperative extension recommendations. They found that adoption of the extension service recommendations not related to the programme was increased 11%. They concluded that the community-wide participation served a much needed communication link that facilitated technology transfer.

PBW area-wide management programme maintenance

Assuming PBW area-wide management is successful, the requirement for long-term monitoring and the continuing maintenance of barriers or buffer zones and applicable control methods is highly controversial. The objections are based on the cost involved and the perception that when maintenance is required it indicates that the tactics used in the area management programme were inadequate initially or have become less effective during use in the programme. Arguments in support of long-term maintenance suggest that the cost of maintaining an effective barrier is not likely to exceed a small percentage of the losses the pest would cause if not controlled. In addition, if a long-term maintenance programme alleviates the need for intensive and extensive use of ecologically disruptive insecticides there would be added benefits. The matter is controversial but the objections may be unjustified if PBW area-wide management is technically and operationally feasible and advantageous from economic and environmental standpoints. These impasses may only be dealt with following a more complete understanding of the factors affecting PBW dispersal and an evaluation of actual area-wide programmes.

Conclusions

In the PBW-infested cotton areas of Arizona and California, some of the available IPM methods are being implemented farm by farm or in limited community-action programmes. Cotton scouting is practised and pheromone trapping and boll sampling are used to determine, to a greater or lesser extent, the need for control based on established action thresholds. The additional control methods described herein can improve current management systems and be incorporated with other IPM components to expand the system to an area-wide dimension. The existing tactics for achieving a high degree of suppression of established native populations are well advanced (Henneberry, 1986) (Fig. 2) and well within the range of practical feasibility for implementation. The potential long-term benefits of PBW area-wide management appear to justify regional efforts to reduce costs, obtain more effective control, produce less environmental contamination and avoid other peripheral problems associated with local uncoordinated efforts that have not reduced the economic status of PBW populations.

Overwhelming evidence from PBW research in the United States identifies the length of the growing season as it relates to the number of PBW-susceptible immature cotton bolls after the onset of diapause as the major factor that determines year after year maintenance of economic population levels. This may not be true in parts of the world where PBW diapause does not occur, but in the southwestern cotton-growing areas of the United States over 95% of the diapause larvae develop in immature bolls after 15 September. Area-wide management should focus on this key aspect of the PBW life cycle, as a base, with the integration of other control methods as needed.

A basic management system with a high probability of acceptable efficacy would include the following.

(1) Uniform planting dates determined by heat unit accumulations for the area involved.
(2) Gossyplure-baited trap monitoring beginning before flower-bud formation.
(3) In-season boll sampling for PBW larvae.
(4) Irrigation termination by 15 August.
(5) Defoliation with the option of a plant growth regulator to abscise green bolls <2.5 cm in diameter between 1 and 15 September.
(6) Stalk shredding, discing and plough down of crop residue as soon as possible after harvest but no later than 1 November.
(7) Winter irrigation where economically feasible.
(8) Yearly crop rotation, never planting cotton following cotton.

Behavioural control with pheromones, transgenic cotton, augmentative biological control and in-season insecticidal control can be superimposed on this management system as determined by PBW infestation levels and economic viability. The suggested calendar dates for irrigation termination, defoliation and crop plough down are those that research has shown to achieve the maximum impact for reducing overwintering PBW populations. Cotton growers have to make the decision for implementation based on a voluntary short-season yield reduction of approximately 5% balanced against the increased costs of insecticides, irrigation and other farm input in full-season production. Economic analysis suggests that short-season cotton is a more profitable alternative (Burrows *et al*., 1984).

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